STRUCTURAL ASSEMBLY DEMONSTRATION EXPERIMENT

PHASE I

Final Report for Contract Number NAS8-34501

March, 1983

SSL#10-83

David L. Akin
Mary L. Bowden

(NASA-CR-193967) STRUCTURAL ASSEMBLY DEMONSTRATION EXPERIMENT, PHASE 1 Final Report, Jul. 1981 - Apr. 1982 (MIT) 69 p

N94-35484

Unclas

G3/18 0013758

SSL

SPACE SYSTEMS LABORATORY
DEPT. OF AERONAUTICS AND ASTRONAUTICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MA 02139

STRUCTURAL ASSEMBLY DEMONSTRATION EXPERIMENT

PHASE I

Final Report for Contract Number NAS8-34501

March, 1983 SSL#10-83

David L. Akin
Mary L. Bowden

STRUCTURAL ASSEMBLY DEMONSTRATION EXPERIMENT

PHASE I

FINAL REPORT FOR CONTRACT NUMBER NAS8-34501

Document Number SSL 10-83

March, 1983

David L. Akin
Mary L. Bowden

Prepared for the
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

by the
Space Systems Laboratory, 33-407 MIT
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139

Principal Investigators:
Professor Rene H. Miller
Professor David L. Akin

I. INTRODUCTION

This report summarizes the work performed by the MIT Space Systems Laboratory under contract NAS8-34501, for the NASA Marshall Space Flight Center, in support of the program entitled "Structural Assembly Demonstration Experiment (SADE)." This contract extended from July 1981 to April 1982. Work was supervised by two Principal Investigators: Professor Rene H. Miller (617-253-2263), and Professor David L. Akin (617-253-3626).

The goal of this phase of the SADE program was to begin to define a Shuttle flight experiment that would yield data to compare on-orbit assembly operations of large space structures with neutral buoyancy simulations. In addition, the experiment would be an early demonstration of structural hardware and human capabilities in Extra-vehicular Activity (EVA). The objectives of the MIT study, as listed in the Statement of Work, were:

1. To provide support in establishing a baseline neutral buoyancy testing data base,
2. To develop a correlation technique between neutral buoyancy test results and on-orbit operations,
3. To prepare the SADE Experiment Plan (MSFC-PLAN-913).

Unfortunately, the neutral buoyancy test series at MSFC were cancelled due primarily to design changes of the structural hardware to be used in the experiment. Consequently, it was not possible to perform task 1 listed above. Work was performed extensively on tasks 2 and 3, however, and this is described below.

II. SUMMARY OF WORK PERFORMED

The work performed under this contract can be divided into the following categories:

1. Neutral buoyancy and flight hardware definition
2. Correlation effort and development of dynamical scaling theory
3. Preparation of the Langley Conference presentation and the SADE Experiment Plan.

Each of these sections is described in more detail below.

1. SADE HARDWARE DEFINITION

The SADE structure consists of two deployable modules connected by an interconnect cell made up of eight individual struts (see figure 1). This interconnect cell is to be manually assembled in order to obtain productivity data for people working in EVA, and to provide a correlation of neutral buoyancy with on-orbit operations. The first task in this study was to identify optimal characteristics of the SADE structural elements to yield the most meaningful data. Analysis and early MIT tests showed that struts should be designed with a variety of moments of inertia, and should be joined using a variety of structural connectors. Four different values of moments of inertia were calculated, two values for the shorter longitudinal elements, and two values for the longer diagonal elements. In addition, five structural connectors were identified as the most interesting for use on the manually assembled section of the structure: the Langley connector, the Rockwell ball and socket connector, the Vought module to module connector, the Vought clevis coupler, and the MIT EVA connector. The number and placement of the connectors is to be determined based on neutral buoyancy development simulations, which will define the assembly procedure. A first cut at the assembly procedure was drafted during the course of this contract, but neutral buoyancy tests are necessary to decide on the best procedures to be used in flight.

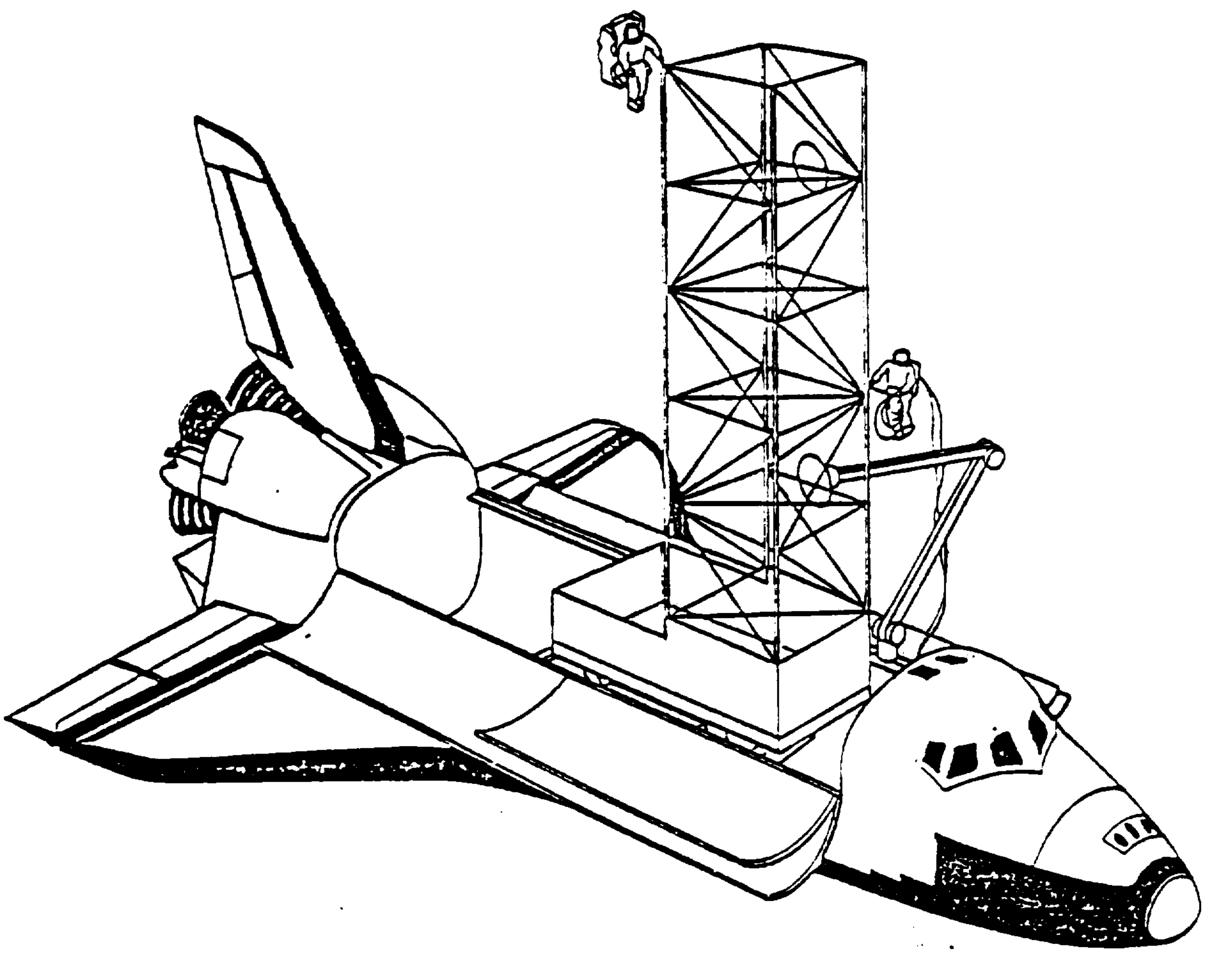


FIGURE 1 - SADE STRUCTURE

2. CORRELATION BETWEEN NEUTRAL BUOYANCY AND ORBITAL OPERATIONS

One of the primary purposes of this experiment is to obtain data for the calibration of neutral buoyancy simulations. This data falls into four categories: time and motion data, body and beam dynamics data, strain gage data, and qualitative crew comments. Time and motion data will consist of detailed tables of times established for each assembly task and subtask both underwater and on-orbit. Thus, quantitative factors relating operations in the two environments can be calculated, and statistical methods can then be used to identify trends and general relationships that apply to other types of tasks and to future missions. To facilitate data aquisition for this study, a "multi-task time and motion timer" has been designed so that a single test observer can keep track of all of the task times during a test run.

Body and beam dynamics data will be obtained primarily from videotapes and movie film shot during the flight. This will be compared to similar footage from neutral buoyancy tests performed either before or after the flight. In addition, the data will be used to evaluate the validity and applicability of MIT computer models that have been developed to simulate the motions of a person and a structural element in space.

Strain gage data will be used to calculate the loads imposed on the structure throughout the assembly procedure by crew translations on the structure, by RMS manipulations, or by Shuttle thruster firings. This data will be obtained by installing several "black boxes" on the structural elements, that will record readings from the strain gages for later analysis and correlation with similar data obtained in neutral buoyancy. The meaning of peaks on this recording will be deciphered with the help of crew comments recorded simultaneously during the run. These comments will also shed some light on many of the other aspects of correlating flight operations with neutral buoyancy.

3. PREPARATION OF SADE EXPERIMENT PLAN

A number of iterations were performed on the SADE Experiment Plan document during the course of this contract. In addition, MIT personnel participated in a presentation of SADE progress at a Large Space Structures Conference at Langley Field, VA. To help prepare for this technical briefing, a finite element analysis of the SADE structure was performed to determine the lowest natural modes and frequencies. The dynamics of individual elements of the truss were also considered in more detail. The material presented at this conference is shown in Appendix A. The final version of the SADE Experiment Plan, that details the most up-to-date information on the SADE flight experiment, is included as Appendix B. The topics covered in this document are listed below:

1. Experiment Objectives
2. Experimental Approach
3. Data Acquisition
4. Data Analysis
5. Benefits from SADE

III. CONCLUSIONS

The SADE appears to be a very worthwhile experiment for obtaining both simulation correlation and structural dynamics data on-orbit. For optimum data return, it is very important to maximize the amount of crew involvement in the EVA, and to insure that their tasks are as challenging as possible. It would also be advantageous to make use of both the Remote Manipulator System and the Manned Maneuvering Unit as much as possible, to maximize data return on human/machine interactions in EVA. A good deal of structural dynamics data can be obtained from this experiment as well, by properly instrumenting the structure and picking a data storage system that can process and record adequate amounts of data. Other aspects of this experiment, such as aquiring thermal data and testing deployable mechanisms for structures, will also contribute to making this experiment a significant and logical step in the development of more ambitious manned activities on-orbit.

APPENDIX A

SADE EXPERIMENT DESIGN

Langley Conference

STRUCTURAL ASSEMBLY DEMONSTRATION EXPERIMENT (SADE)

EXPERIMENT DESIGN

D. L. Akin and M. L. Bowden
M.I.T. Space Systems Laboratory
Cambridge, Massachusetts

Large Space Systems Technology - 1981
Third Annual Technical Review
November 16-19, 1981

SADE Experiment Design

Operating as a contractor to the Marshall Space Flight Center, the Space Systems Laboratory of the Massachusetts Institute of Technology is responsible for the design and analysis of the experimental studies which make up the Structural Assembly Demonstration Experiment (SADE). The following paper summarizes the presentation given by Dr. D. L. Akin and M. L. Bowden at the Third Annual Technical Review of Large Space Systems Technology, 1981. This was given in conjunction with the presentation "Structural Assembly Demonstration Experiment (SADE)", by H. Watters and J. Stokes of NASA Marshall Space Flight Center. The SADE concept is to erect a hybrid deployed/assembled structure as an early space experiment in large space structures technology.

SADE Objectives

The basic objectives can be broken down into four generic areas.

Simulation Correlation: By performing assembly tasks both in space and in neutral buoyancy simulation, a mathematical basis will be found for the validity conditions of neutral buoyancy, thus enhancing the utility of water as a medium for simulation of weightlessness.

Human Factors: A data base will be established describing the capabilities and limitations of EVA crewmembers, including effects of such things as hardware size and crew restraints.

Structural Data: Experience of the M.I.T. Space Systems Lab in neutral buoyancy simulation of large space structures assembly indicates that the assembly procedure may create the largest loads that a structure will experience during its lifetime. Data obtained from the SADE experiment will help establish an accurate loading model to aid designers of future space structures.

Thermal Data: The size of the proposed SADE structure presents an opportunity for auxiliary experiments. With the SADE structure as a support, a large heat pipe will be tested for efficiency in space, free from the thermally restrictive environment of the payload bay.

SIMULATION CORRELATION

HUMAN FACTORS

STRUCTURAL DATA

THERMAL DATA

Task Correlation

The primary objective of the SADE program is to correlate actual EVA experience with identical task performance in a neutral buoyancy simulator. Neutral buoyancy is the only method possible on earth for simulation of structural assembly activities in space, due to the size of the elements and the time necessary for assembly. This chart relates the data collection and analysis methods to be used in this section of the study.

METHODS:

- VIDEO TAPE STRUCTURAL ASSEMBLY OPERATIONS USING CCTV CAMERAS MOUNTED ON FORWARD STARBOARD AND AFT PORT CARGO BAY BULKHEADS.
- POST-FLIGHT TIME AND MOTION STUDIES OF EVA OPERATIONS BASED ON VIDEO TAPES, TIME LAPSE MOVIE (1 FPS, WIDE ANGLE LENS, STARBOARD WINDOW AFT FLIGHT DECK), AND INTERMITTENT MOVIE FOOTAGE BY EVA CREW MEMBERS.
- COMPARISON BASED ON TASK TIMES (EXAMPLE TASKS: TRANSLATION, ALIGNMENT, CONNECTION) AND SUBTASK TIMES (EXAMPLE SUBTASKS: UNSTOW INTERCONNECT BEAM #3) TO PREVIOUS NEUTRAL BUOYANCY TESTS PERFORMED WITH SAME CREW MEMBERS AND SAME TIME LINES.
- POSSIBILITY OF POST-FLIGHT NEUTRAL BUOYANCY SIMULATIONS FOR ADDITIONAL COMPARISON DATA BASE.

Results of Task Correlation

The result of primary importance from this section of the SADE experiment is the establishment of a quantitative correlation between earth-based assembly simulations and on-orbit operations. This will result is a set of correlation factors applicable to similar tasks performed in the future; these factors will allow the experiment designer to do mission planning with confidence in the applicability of neutral buoyancy simulation results to actual EVA operations. In addition, the effects of water drag on subject motion will be studied by direct comparisons of neutral buoyancy and EVA experience.

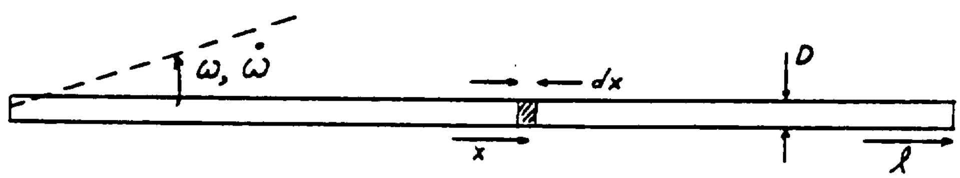
RESULTS:

- QUANTITATIVE CORRELATION OF TASK TIMES IN NB SIMULATION WITH ACTUAL TASKS IN SPACE.
- DEVIATION OF INDIVIDUAL SUB-TASK TIMES FROM TASK AVERAGES IN BOTH NB AND SPACE, INDICATING RELIABILITY OF DATA.
- QUALITATIVE INVESTIGATION OF UNDERWATER SIMULATION VALIDITY BASED ON SIMULTANEOUS TASK REVIEW (SPLIT-SCREEN VIDEO TAPES OF SAME SUB-TASK, FROM SAME CAMERA POSITION COMPARING CREW MEMBER BODY REACTIONS UNDERWATER TO THOSE IN SPACE).

Dynamic Model Correlation

The preceeding correlation technique applies to identical tasks: that is, the structural elements used in simulations underwater are high fidelity flight configuration mockups, except for modifications necessary to insure neutral buoyancy. The difference in dynamics between space and underwater for such hardware can best be illustrated by a long cylindrical beam rotating at an angular velocity ω and an acceleration of $\dot{\omega}$. As can be seen below, the inertia force scales as the cube of the length, while the drag force is dependent on both the fourth power of the length, and the square of the angular velocity. The net effect is that the total torque which must be applied for rotation underwater is the sum of the inertial and viscous torques, and, as a result, handling a beam underwater requires greater effort than in space.

FOR A NEUTRALLY BUOYANT, DISTRIBUTED MASS BEAM:



TORQUE DUE TO:

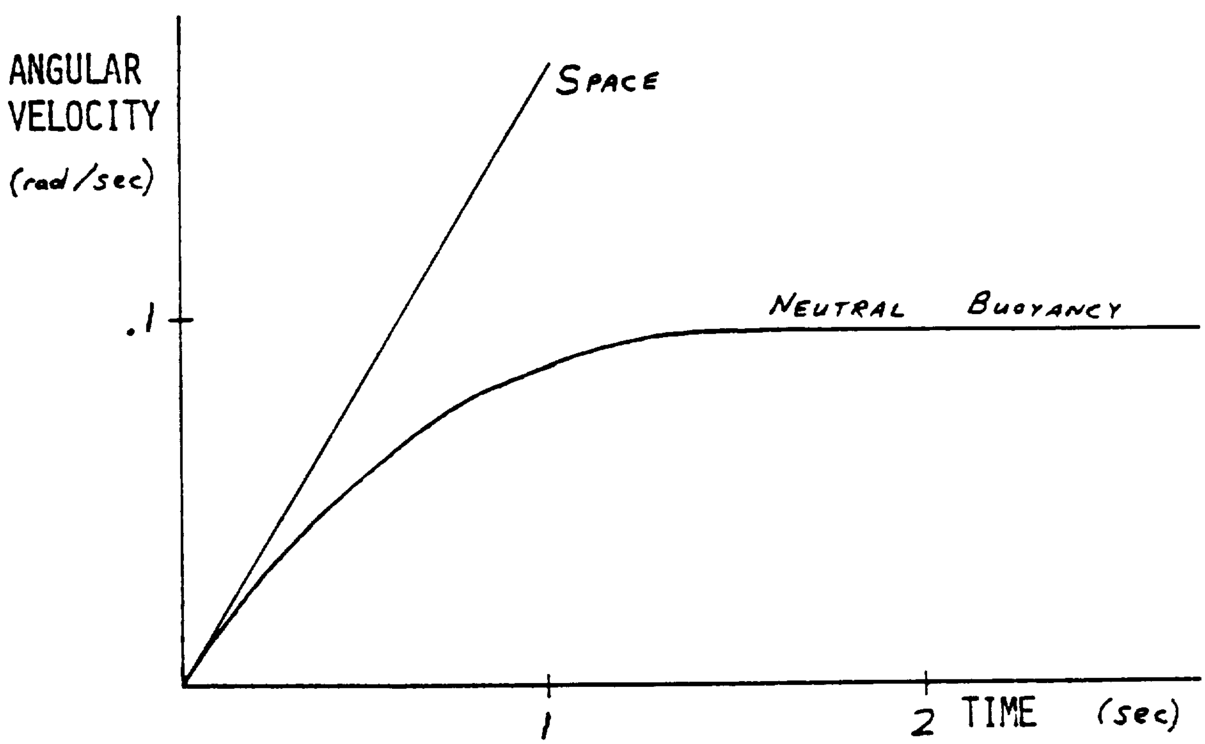
$$\begin{cases} \text{INERTIA: } \displaystyle\int_0^{l} \frac{\rho}{4}\,\dot{\omega}\,D^2 x^2\,dx \\ \text{DRAG: } \displaystyle\int_0^{l} C_D \frac{\rho}{2}\,\omega^2 D\,x^3\,dx \end{cases}$$

$$T = \underbrace{\frac{\rho}{12} D^2 l^3 \dot{\omega}}_{\text{INERTIAL}} + \underbrace{\frac{\rho}{8} C_D D l^4 \omega^2}_{\text{VISCOUS}}$$

Dynamics Example

In order to demonstrate the effect of the preceeding equations, exact solutions have been found for the differential equations, and the results are plotted here for a typical beam, such as a component of the SADE interconnect cell. As can be seen, the angular velocity increases rapidly and linearly at a constant applied torque, as would be expected in the absence of other forces. The same beam underwater, on the other hand, reaches terminal velocity within 2 seconds, and will not accelerate unless additional torque is applied. The significant discrepancy between the two curves emphasizes the inaccuracy in dynamics when flight configuration hardware is used for neutral buoyancy tests.

INTERCONNECT DIAGONAL
STAINLESS STEEL BEAM
7.5 N M TORQUE APPLIED



Dynamic Model Correlation

In order to reduce the error evident in the previous graph, it has been proposed to design neutral buoyancy hardware based on an "effective moment of inertia", which is composed of both inertial and drag terms. Within a range of assumed rotation velocities and accelerations, such a dynamically scaled component would require approximately the same total effort to rotate through a given angle in a given amount of time as the actual component in space. Under these conditions, neutral buoyancy simulations should directly correspond to the on-orbit timelines for medium-critical tasks such as alignment. In order to achieve this dynamic scaling, the component size and mass must be significantly reduced from the flight configuration: the reduction in inertia is compensated for by drag effects.

METHODS:

- DYNAMICALLY SCALED INTERCONNECT HARDWARE
  - MINIMIZE DRAG, VIRTUAL MASS.
  - DESIGNED SO THAT EFFORT REQUIRED TO ALIGN BEAM UNDERWATER ("EFFECTIVE MOMENT OF INERTIA") IS EQUAL TO EFFORT REQUIRED FOR THE SAME ALIGNMENT TASK IN SPACE.
- PRIMARY TRAINING AND DATA BASE COLLECTION WILL USE FLIGHT CONFIGURATION HARDWARE TO PROVIDE PROCEDURES TRAINING AND DIRECT TASK CORRELATION BACKGROUND.
- DATA RETURN FROM FLIGHT IS AMPLIFIED BY SIMPLE ADDITIONAL TASKS.
  - BEAM ROTATION PERPENDICULAR TO CAMERA ALLOWS MEASUREMENT OF ANGULAR RATES.
  - DIFFERENT MOMENTS OF INERTIA OF INTERCONNECT BEAMS PROVIDE ADDITIONAL DATA.

SADE Structural Component Characteristics

Since the SADE project represents a unique opportunity to get a correlation data base for comparing component dynamics underwater and in space, it is important to maximize data return. For this reason, the eight individual elements of the interconnect structure have been designed to provide four discrete levels of moment of inertia. Design details of the interconnect beams are presented below, along with similar details for the elements of the deployable modules.

		RADIUS	THICKNESS	LENGTH	MASS	MOMENT OF INERTIA
DEPLOYED MODULE	LONGITUDINALS	3.175	0.089	300	1.438	4.31
	LATERAL/ VERTICALS	1.588	0.159	300	1.285	3.85
	DIAGONALS	1.588	0.159	424	1.816	10.88
INTERCONNECT	LIGHT LONGITUDINAL	1.905	0.089	300	0.844	2.53
	LIGHT DIAGONAL	1.905	0.089	424	1.193	7.15
	HEAVY LONGITUDINAL	1.905	0.635	300	14.907	44.72
	HEAVY DIAGONAL	1.905	0.635	424	21.069	126.25
UNITS		cm	cm	cm	kg	kg m^2

Results of Dynamic Model Correlation

At the completion of this effort, a validated mathematical model of component dynamics in both space and water will exist. By using this model, a researcher can design a set of hardware, representing a dynamic analogue of the flight hardware. Simulations performed using this dynamic hardware underwater should give a close estimate of actual timelines for assembling flight hardware in space.

This technique should not be viewed as negating the importance of the direct task correlation data obtained using identical hardware underwater and in space. Correlation of neutral buoyancy results using flight configuration hardware will remain vitally important, as procedures development and crew training will demand high fidelity hardware. Rather, this scaling technique should be considered a useful tool for the neutral buoyancy researcher. By using dynamically scaled components, for example, a structure much too large to fit into a neutral buoyancy facility in flight configuration can still be tested underwater to arrive at procedures and timelines estimates, thus increasing the utility of existing simulator facilities.

RESULTS:

- A VALIDATED MATHEMATICAL MODEL OF STRUCTURAL COMPONENT DYNAMICS IN SPACE AND IN NEUTRAL BUOYANCY SIMULATION.
- CAPABILITY TO DESIGN A NEUTRAL BUOYANCY STRUCTURE MOCKUP WHICH WILL FEEL (IN TERMS OF EXPENDED EFFORT) SIMILAR TO THE DESIRED FLIGHT DESIGN.
- EXPANSION OF THE USEFULNESS OF NEUTRAL BUOYANCY, AS STRUCTURES UNDERWATER SIMULATE MUCH LARGER STRUCTURES IN SPACE.

Human Factors Hardware

The second generic area covered by the research objectives of SADE is that of human factors. This includes studies such as the effects of mass and moment of inertia, connector design, the requirements and role of body restraints, and integrated use of the manned maneuvering unit (MMU) and the shuttle Remote Manipulator System (RMS). Much of this data will be collected during the assembly of the interconnect structure, which is a set of eight beams connecting the two two-cell deployable modules. This chart lists the characteristics of the structural elements for this cell.

- STRUCTURAL CONNECTORS
- LIGHT LONGITUDINAL MEMBERS (2) (LL)
  - 3M LONG, ALUMINUM
  - .8 KG
- LIGHT DIAGONAL MEMBERS (2) (LD)
  - 4.2 M LONG, ALUMINUM
  - 1.2 KG
- HEAVY LONGITUDINAL MEMBERS (2) (HL)
  - 3 M LONG, STAINLESS STEEL
  - 14.9 KG
- HEAVY DIAGONAL MEMBERS (2) (HD)
  - 4.2 M LONG, STAINLESS STEEL
  - 21.1 KG

Structural Connector Characteristics

In order to evaluate connector design, different structural connectors will be mounted on the eight individual beams of the interconnect cell. Relative details of the five connectors chosen are shown in this figure. "Angular tolerance" relates to the required accuracy of the alignment before mating connector parts meet. The actual connection procedure is somewhat arbitrarily broken down into three segments: "capture" (whether or not the connections are coupled upon initial contact, "rigidizing" (regarding the existence or not of a discrete operation required to rigidize the joints), and "latching" (whether or not a discrete step is required for the final locking). Since the SADE structure must also be disassembled for stowage prior to entry, note is taken of whether or not a release tool is required for releasing the connection. It is desirable in this study to have a wide assortment of connector types in the experiment; this particular selection adequately spans the range of characteristics, while eliminating the need for new joint development.

		MSFC Ball & Socket	LARC Snap Union	MIT Connector	Vought Clevis Coupler	Vought Autolock Coupler
Angular Tolerance	High	●			●	●
	Low		●	●		
Capture	Yes	●	●		●	●
	No			●		
Rigidizing	Yes	●				
	No		●	●	●	●
Latching	Yes			●		
	No	●	●		●	●
Release Tool	Yes	●				
	No		●	●	●	●

Assembly Crew Assignments

As currently envisioned, four crew members will be associated with conducting the SADE experiment. Two will be the EVA test subjects, with considerable prior experience in neutral buoyancy. Another crew member will operate the manipulator arm and follow EVA activities with shuttle closed circuit television (CCTV) cameras during periods when the RMS is not operating. The fourth crew member will serve as the test director, reading checklists to the EVA crew, and additionally will assist in CCTV operations and serve as interior documentary photographer with hand-held still and movie cameras. It is recognized that the work load for the crew on the aft flight deck will probably be higher than that of the EVA crew, in number if not in difficulty of tasks.

ASSEMBLY CREW ASSIGNMENTS

- Two EVA crew members
  - One with manned maneuvering unit (subject A)
  - One unaided (subject B)

- One RMS operator (port station, aft flight deck)
  - Also primary video/CCTV operator

- One test director (starboard station, aft flight deck)
  - Also secondary video/CCTV operators
  - Also documentary photographer (stills/movies)

Assembly Procedure

As part of the planning procedure for the SADE experiment, a "strawman" assembly procedure was decided upon. That procedure, which is being recommended for initial neutral buoyancy tests by the M.I.T. study team, is presented over the next three pages as representative of a typical assembly procedure outline. While it is felt that this particular procedure is near-optimal in terms of data collected, it has not yet passed through safety review, and should not be misconstrued as an approved baseline.

The procedures listing begins with the start of the assembly tasks, and does not include standard EVA procedures, such as egress, MMU donning, and so forth. Of special note here is step 2, in which the subject in foot restraints faces a camera on the forward bulkhead (standard CCTV and/or aft flight deck movie cameras) and rotates the beam in a plane perpendicular to the line of sight of the camera. Starting with the beam parallel to the orbiter y-axis, it is rotated to a stop parallel to the z-axis, then accelerated and decelerated through another 90 degrees. The beam is then rotated back to its initial position, without the intermediate stop, and then placed into the structure. While this may seem to be a "mindless" experiment, it is actually critical to some of the human factors testing. By finding beam position as a function of time, estimates of human control laws and torquing capabilities can be made. This data will be of prime importance for determining the optimum role of humans in future space operations.

TASK	DATA OBTAINED ON
(1) Unstow two elements of interconnect cell (LL, LD)	EVA operations
(2) Rotate each element through 90° and 180° in front of camera	Human control laws & torque levels Effect of mass and moment of inertia (with foot restraints)
(3) Install interconnect elements on folded module 1	Assembly in foot restraints Connector design
(4) Repeat steps (1), (2), and (3) for two more elements of interconnect cell (HL, HD)	(as listed above)
(5) Engage grapple fixture on module 1 with RMS	RMS operations
(6) Release module 1 launch restraints	EVA operations
(7) Deploy module 1 (cells 1 and 2) with RMS	RMS deployment capability

Assembly Procedure

The primary thrust of this section of the assembly procedure is to test the capabilities of an unrestrained test subject. Both subjects are required to translate, either hand over hand along the structure or with MMU, while carrying a structural element, and then install this element at the top of the deployed module. The same motion is performed with the beams before they are connected, so that the subject's ability to control his body position can be evaluated. Each subject will be required to do this exercise twice, once with a light beam and once with a heavy beam, so that the effect of mass and moment of inertia on assembly dynamics and human control laws can again be evaluated.

TASK	DATA OBTAINED
(8) UNSTOW 2 MORE ELEMENTS OF INTERCONNECT CELL (LL, LD)	EVA OPERATIONS
(9) SUBJECT B TRANSLATES ALONG MODULE 1 WITH LL ELEMENT	MANUAL TRANSLATION WITH HARDWARE ASSEMBLY LOADS
(10) SUBJECT A MOVES TO WORKSITE AT TOP OF MODULE 1 WITH LD	MMU TRANSLATION WITH HARDWARE
(11) SUBJECTS ROTATE ELEMENTS THROUGH 90° AND 180° IN FRONT OF CAMERAS	HUMAN CONTROL LAWS & TORQUE LEVELS EFFECTS OF MASS & MOMENT OF INERTIA (WITHOUT FOOT RESTRAINTS)
(12) CONNECT ELEMENTS TO TOP OF MODULE 1	ASSEMBLY WITHOUT BODY RESTRAINTS ASSEMBLY LOADS
(13) SUBJECTS TRANSLATE BACK TO LAUNCH ASSEMBLY PLATFORM	UNENCUMBERED MANUAL TRANSLATION UNENCUMBERED MMU TRANSLATION ASSEMBLY LOADS
(14) - (19) REPEAT STEPS (8) THROUGH (13) WITH REMAINING 2 ELEMENTS OF INTERCONNECT CELL (HA AND HL)	(AS LISTED ABOVE)

Assembly Procedure

This section of the assembly procedure is especially notable because it briefly tests the whole gamut of space assembly techniques:

- fully manual operations - as test subject B deploys the first cell of the deployable module (step 23)
- augmented manual operations - as test subject A, using the MMU for power, deploys the second cell of the deployable module (step 24)
- teleoperator operations - as the RMS is used to rotate module 1 and position it accurately above module 2 (step 26)

TASK	DATA OBTAINED
(20) SUBJECTS RELEASE MODULE 1 HOLDDOWNS	EVA OPERATIONS
(21) RMS MOVES MODULE 1 AND INTERCONNECT CELL UP, AFT, AND OUTBOARD PORT	MANIPULATION OF HIGH MOMENT OF INERTIA, LIGHTWEIGHT STRUCTURE WITH RMS
(22) RELEASE MODULE 2 LAUNCH RESTRAINTS	EVA OPERATIONS
(23) SUBJECT B DEPLOYS MODULE 2, CELL 1, MANUALLY	USE OF UNAIDED EVA FOR DEPLOYMENT
(24) SUBJECT A DEPLOYS MODULE 2, CELL 2, USING MMU	USE OF MMU FOR DEPLOYMENT
(25) SUBJECT B TRANSLATES TO TOP OF MODULE 2	UNENCUMBERED MANUAL TRANSLATION
(26) RMS ROTATES MODULE 1 180° AND BRINGS IT INTO POSITION OVER MODULE 2	MANIPULATION OF HIGH MOMENT OF INERTIA WITH RMS
(27) ATTACH INTERCONNECT CELL TO MODULE 2 WITH RMS GUIDED BY EVA CREW	INTEGRATED RMS/EVA ASSEMBLY OPERATIONS

Structural Element Vibration Analysis

Before data recording requirements can be reasonably discussed, some estimates are necessary as to the data sampling rates for structural loading data. In this table, the five most significant vibrational modes (3 cantilever, 2 free-free) of the individual structural elements have been found. Although the natural frequencies of the three types of elements found in the deployable modules have been included for completeness, they tend to respond at structural rather than element frequencies, and the quantities of primary interest are those pertaining to the four types of interconnect beams. The free-free modes are those likely to be excited during transportation of the beams to the work site: cantilever modes are found during the interconnect structural assembly procedure. If the first cantilever mode is the only one of interest, waveform reconstruction can be accomplished using a sampling rate of the order of 10-15 Hz, except for the light longitudinal beam, which would require 20-30 Hz. If the first free-free mode is also taken into account, sampling requirements would increase to 100 Hz, and the second cantilever mode would also be covered. Since this would have to triple (300 Hz) in order to include the second free-free and third cantilever modes, the design sample rate for this criteria will be considered to be 100 Hz, incorporating only the first three structural modes.

		1ST CANTILEVER	2ND CANTILEVER	3RD CANTILEVER	1ST FREE-FREE	2ND FREE-FREE
DEPLOYED MODULE	LONG.	2.798	17.539	49.114	17.818	49.101
	LAT./ VERT.	1.325	8.307	23.261	8.439	23.255
	DIAG.	0.664	4.164	11.661	4.231	11.658
INTERCONNECT	LT. LONG.	1.673	10.488	29.370	10.655	29.362
	LT. DIAG.	0.840	5.266	14.747	5.350	14.743
	HVY. LONG.	0.854	5.354	14.993	5.439	14.989
	HVY. DIAG.	0.429	2.688	7.528	2.731	7.526

Data Recorder Options

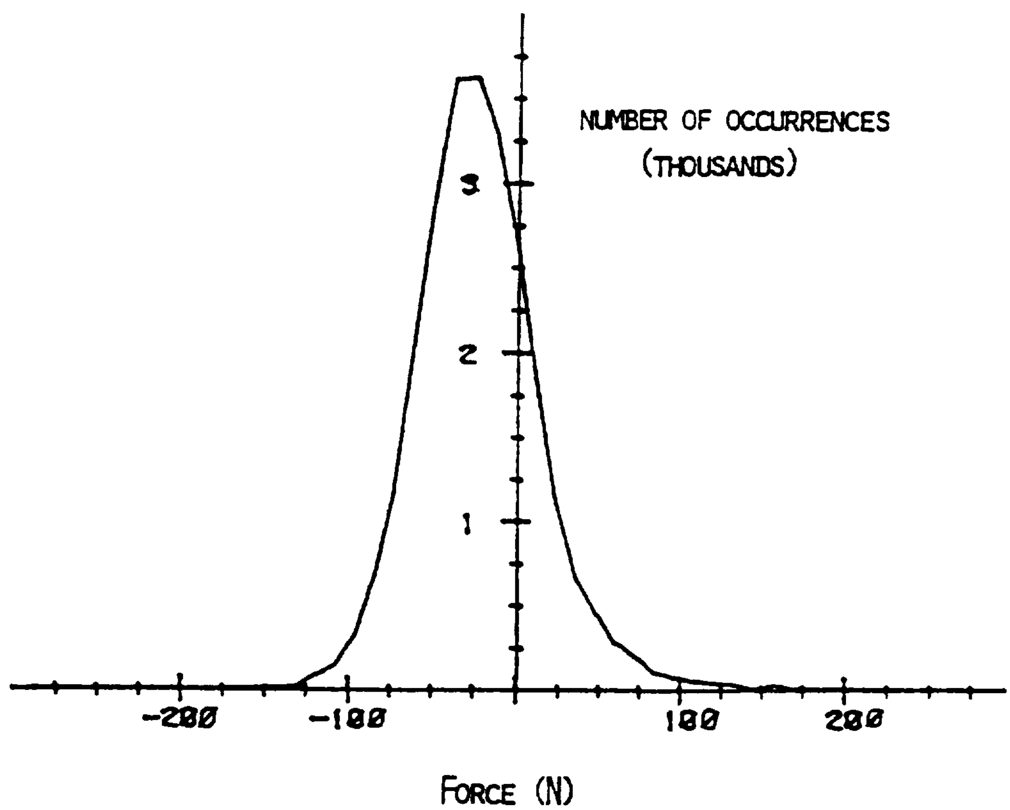
Two options exist for flight data recorders: a data system developed by NASA Langley for experiments on the long duration exposure facility (LDEF), and a solid-state recorder under development by M.I.T. The LDEF Experiment Power Data System has the advantage of being an "off-the-shelf" unit, and thus represents the lower technological risk. It is a central unit, which would be mounted on the SADE Launch Assembly Platform (LAP), and record signals brought in through wires from sensors distributed around the structure. The disadvantage of this, of course, is that no connections exist to sensors in the top module or interconnect cell until after the structure is complete and wires can be run to those areas. While the wiring integration is a worthwhile human factors task in itself, this would prevent the acquisition of assembly loads on most of the structure. The M.I.T. Solid-State Self Contained Recorder (SSSCR) must be flight qualified, but represents the other extreme of a separate recorder for each data signal, distributed around the structure. The use of many such dedicated sensor/recorder packages insures that most of the data is returned, even if some of the units fail.

- LDEF Experiment Power Data System
  - Central recording of distributed sensors
  - 14 MB of storage
  - Developed technology

- Solid-State Self Contained Recorder
  - Under development by MIT SSL
  - Dedicated sensor/recorder package
  - Highly Redundant

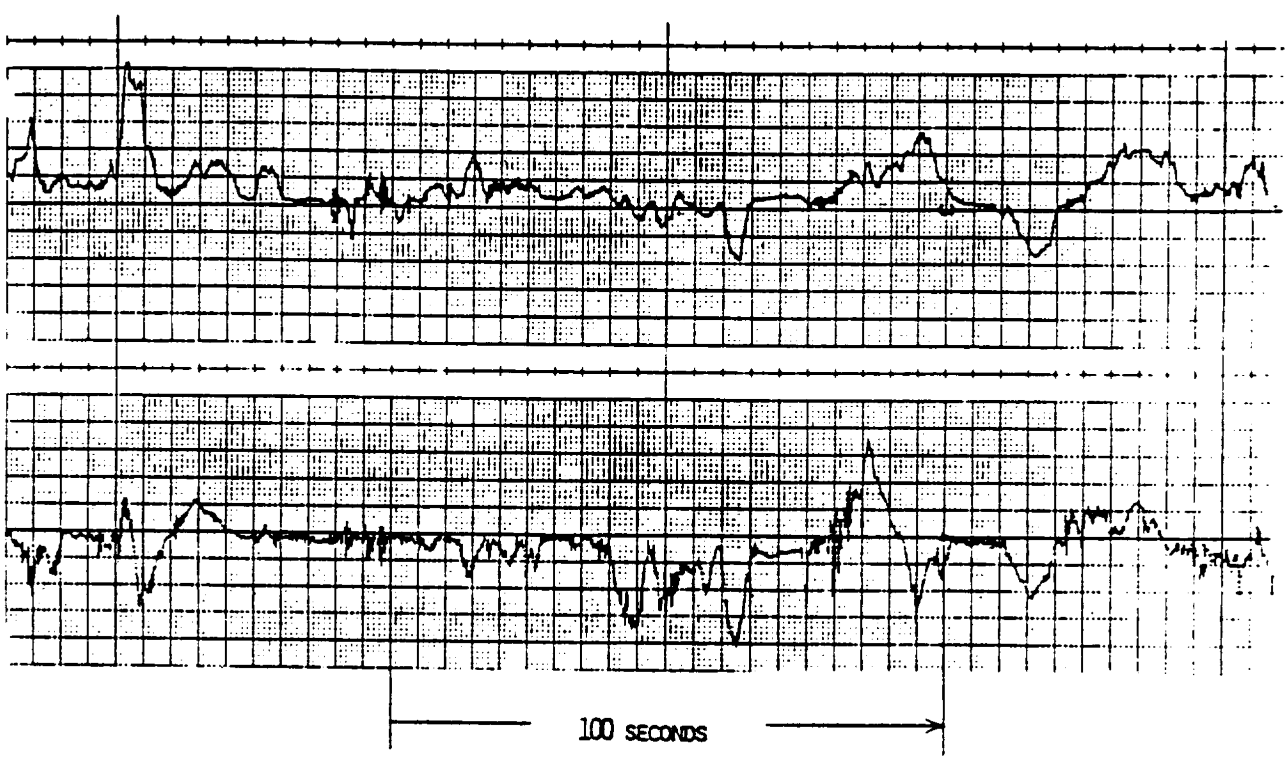
Sample Strain Gauge Results

This graph illustrates the distribution of load levels on a structural element during a neutral buoyancy assembly procedure. The number of times a given load level (positive for tension; negative for compression) occurred in the beam during the assembly is plotted against that load level. Thus, one can see, for example, that the beam was in compression during most of the assembly, but the highest loads, which were quite infrequent, were tension loads. This is probably not true in general, of course, but it does illustrate the type of information one can obtain from a recording of the strain levels in a beam.



Sample Strain Gauge Data

This sample of strain gauge data (obtained during assembly of a neutral buoyancy structure) illustrates some of the characteristics that are expected for the data obtained from the SADE experiment. The major peaks appear to be broad enough that even a fairly low sampling rate for the data recording instruments (such as 10 Hz) will be sufficient to pick up the peak loads during assembly. Further analysis of data obtained during early neutral buoyancy tests indicate that for purely manual assembly, the peak loads that a test subject can apply to the structure will be on the order of 300-400 N (tension or compression) and 80-100 Nm (bending moment).



Details of the M.I.T. SSSCR

Activated by an EVA crew member prior to releasing a structural element from the launch restraints, the Solid-State Self Contained Recorder is designed to take readings from colocated strain gauges, convert the strain readings into force and moment applied to the beam, and convert this continuous (analog) signal into the desired form for recording into solid state memory. The unit will be left attached to the structure throughout the flight.

The strain gauge readings are taken from 3 gauges placed at 90° intervals around the beam. The gauges are excited with an AC voltage, and the three strain readings are used to find force and principal moments applied to the beam. This is accomplished through a phase shifting technique, which resolves the magnitude of the moment vector in the complex plane. The data conversion options available include direct wave-form conversion, storing the peak loads which occurred during a set time interval, noting when the loads exceed a preset limit and storing the time of that event, or performing a fast Fourier transform of the waveform, and storing the Fourier coefficients. All of these options will be used, but only one option may be used per recorder. The memory section consists of integrated circuits (programmable read-only memory) which store the information in the form of 8-bit words for post-flight transcription and data reduction.

- STRAIN→STRESS RESOLVER
  - 3 LONGITUDINAL STRAIN GAUGES AT 90° FROM BEAM AXIS
  - AC GAUGE EXCITATION WITH PHASE SHIFTING
    DIRECT ANALOG OUTPUT OF FORCE AND MOMENTS
- DATA CONVERSION OPTIONS
  - DIRECT (WAVE-FORM STORAGE)
  - PEAK LOADS DURING TIME INTERVAL
  - TIME OF THRESHOLD PASSAGE
  - FAST FOURIER TRANSFORM
- MEMORY
  - SOLID STATE (PROM)
  - SIZE OF MEMORY TAILORED TO REQUIREMENTS

Recorder Allocations

The particular assignment of recorder type to each application is a function of the previously listed characteristics of each system. The LDEF EPDS is the recorder of choice for the thermal experiments, and is in fact well suited to this experiment, as the sensor connections can be made during installation of the heat pipe experiment. This is a welcome addition to the EVA tasks list, and will allow additional information on EVA operations. The EPDS is also applicable to structural information return for the lower module, which always remains attached to the cargo bay. This will augment the information return on the design of the deployable modules, as the effect of preinstalled wiring can be verified. Detailed analysis of the type and number of sensors for this unit await a decision on whether or not dedicated EPDS systems will be used for the thermal and strucural experiments, or whether a single recorder will be shared by the two areas.

The M.I.T. SSSCR is well suited to the beams of the interconnect structure and the upper deployed module, as they may be activated prior to component use. Stress readings will then be taken during the assembly procedure, which is one of the prime objectives of the structural experiment. Each interconnect beam will be equipped with two SSSCR units: one will measure peak loads for a design data base, and the other will measure stress waveforms for dynamics and damping studies. Details of unit emplacement on the top deployed module await a detailed investigation of the structural clearances available in the folded configuration.

- LDEF EPDS
  - Thermal experiment
  - Module 2 structural measurements
    - Details await thermal requirements
- MIT SSSCR
  - Interconnect Cell
    - 2/beam (peak loads and waveforms)
- Module 1
  - Usage and placement dependent on stowage clearances

APPENDIX B

SADE EXPERIMENT PLAN

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

STRUCTURAL ASSEMBLY DEMONSTRATION EXPERIMENT (SADE) EXPERIMENT PLAN

MSFC - Form 454 (Rev. October 1976)

SADE EXPERIMENT PLAN

Document Number MSFC-PLAN-913 (SSL 9-82)

April 23rd, 1982

Mary L. Bowden
David L. Akin

Prepared for the
George C. Marshall Space Flight Center
by the
Space Systems Laboratory
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology

1.0 INTRODUCTION

Many large scale space systems envisioned for the next two decades of the US space program rely on the availability of structural platforms as a strongback for mounting scientific experiments, communication antennae, materials processing and fabrication modules, or living quarters. Because of the size requirements for these platforms, they clearly cannot be launched in finished form in the cargo bay of the shuttle orbiter. For this reason, it will be necessary to either deploy or assemble the structure while on orbit. A near term flight experiment to demonstrate these capabilities and to identify potential problems is presented here.

1.1 Purpose

A structural assembly demonstration experiment (SADE) is a critical first step in the development of large space structures. It will help to determine how best to go about assembling structures, and what role crewmen can play in the construction procedure.

The fundamental purposes of SADE are as follows:

1. To establish a quantitative correlation between earth-based assembly simulations and on orbit operations
2. To obtain assembly data relating to orbital assembly with the Manned Maneuvering Unit (MMU) and the Remote Manipulator System (RMS)
3. To study the structural dynamics and thermal characteristics of an intermediate-scale space structure in a realistic environment

1.2 Scope

The purpose of the SADE Experiment Plan is to outline and guide the development of the scientific objectives of this flight experiment. This document details the following tasks:

- Identification of experiment objectives
- Planning of experimental approach
- Data acquisition methods
- Data analysis techniques

1.3 Experiment Rationale

Neutral buoyancy is currently the most effective medium for ground-based simulation and testing of assembly operations. However, in order to have confidence in the validity of the simulation results, it is necessary to have a full understanding of the relationship between neutral buoyancy and on-orbit timelines. Clearly, a near-term flight experiment using hardware previously tested in neutral buoyancy, will yield quantitative correlation factors for a wide variety of assembly-related tasks. In addition, more general insight into the strengths and limitations of neutral buoyancy as a simulation medium can be obtained. It is imperative to have this knowledge if neutral buoyancy is to be used in the future to successfully predict the number of flights, days, and EVA sorties necessary to complete the construction of a larger scale space platform.

The second fundamental purpose of this experiment is to obtain manual assembly data, both quantitative data on such things as productivity, and qualitative data relating to procedures and hardware evaluation. For this reason, the flight structure should be designed from the beginning as an apparatus to be assembled by pressure suited subjects. Once complete, however, it should yield significant scientific and engineering structural data while on-orbit. In addition, this structure should have validity as a space platform in its own right, incorporating hardware which may be a development model for future space systems.

2.0 EXPERIMENT OBJECTIVES

The prime objectives of the Structural Assembly Demonstration Experiment can be subdivided into the following three categories:

1. Simulation Correlation
2. Assembly Factors
3. Structural Study

The objectives of each category are described briefly in this section.

2.1 Simulation Correlation

To correlate neutral buoyancy simulations with on-orbit operations, the first objective is to establish a timeline data base for assembly tasks, then to calculate the correlation factors for each task, and finally to extrapolate these correlation factors to other assembly tasks and structures. In addition to this quantitative analysis, a better understanding of the neutral buoyancy environment will be obtained from this analysis so that the simulation can be improved for future projects.

2.2 Assembly Factors

One objective under this section is to quantify extra-vehicular (EV) kinematics. By studying the motions of both the astronaut and the components manipulated, it is possible to gain a fundamental insight into the physics of extravehicular activity (EVA). By using the on-orbit experience to validate sophisticated computer models, an EVA procedures designer will be able in the future to perform initial neutral buoyancy tests on the computer, saving hardware and test costs, and reducing the load on the highly limited number of neutral buoyancy facilities. A further assembly objective is to evaluate, from the point of view of the user, the structural hardware and peripheral equipment used in this flight experiment, and to identify possible improvements for future use. The key parameters characterizing ease of assembly or deployment will also be identified. (For example, is length or moment of inertia the significant variable for beam alignment?)

2.3 Structural Study

Instrumentation will be installed on the structure to meet the following objectives: the lowest natural frequencies and modes of the structure will be quantified; the loads imposed on the structure by deployment, by EVA assembly, by MMU-augmented assembly, by RMS operations, and by shuttle vernier thrusters will be measured; and damping for the structure as a whole will be analyzed.

Experiment Objectives

3.0 EXPERIMENTAL APPROACH

This section describes the experimental hardware, the preparatory tests prior to the flight, the procedures to be used on orbit, and the post flight data analysis and testing.

3.1 Experimental Hardware

The central part of this flight experiment is to construct and subsequently disassemble a hybrid deployable-erectable structure in the space shuttle cargo bay (see figure 1). The deployable structure chosen is a single-fold double cell module designed by Vought Corporation (see figure 2). Two of these modules will be deployed on orbit and joined together using an interconnect module of eight individually erected structural elements. The erectable structural elements consist of four longitudinal elements and four diagonal elements. In order to study the effect of moment of inertia of a structural element on ease of assembly, two of the longitudinals will be made of lightweight material, and two will be of heavy material; the diagonals will be made in a similar manner. This difference in density will result in significantly different moments of inertia for the eight erectable elements. Table 1 shows the structural characteristics of all the elements of the structure.

Four different connector designs will be used as joints between the eight structural elements and the deployable modules. Sixteen connections will need to be made (two ends for each of eight elements), so there will be four uses of each connector design. Table 2 defines the connectors that are currently being considered for this purpose.

A Launch/Assembly Platform (LAP), will secure the deployable modules in their folded configuration for launch and will also restrain during launch and return all other hardware necessary for this experiment. A flight data recorder will be mounted on the pallet to record structural and thermal data obtained from sensors distributed throughout the structure.

The deployment and assembly of this structure will be performed with the aid of the Remote Manipulator System (RMS), and the Manned Maneuvering Unit (MMU). Both of these assembly aids will be stowed in their usual configuration prior to use.

Experimental Approach

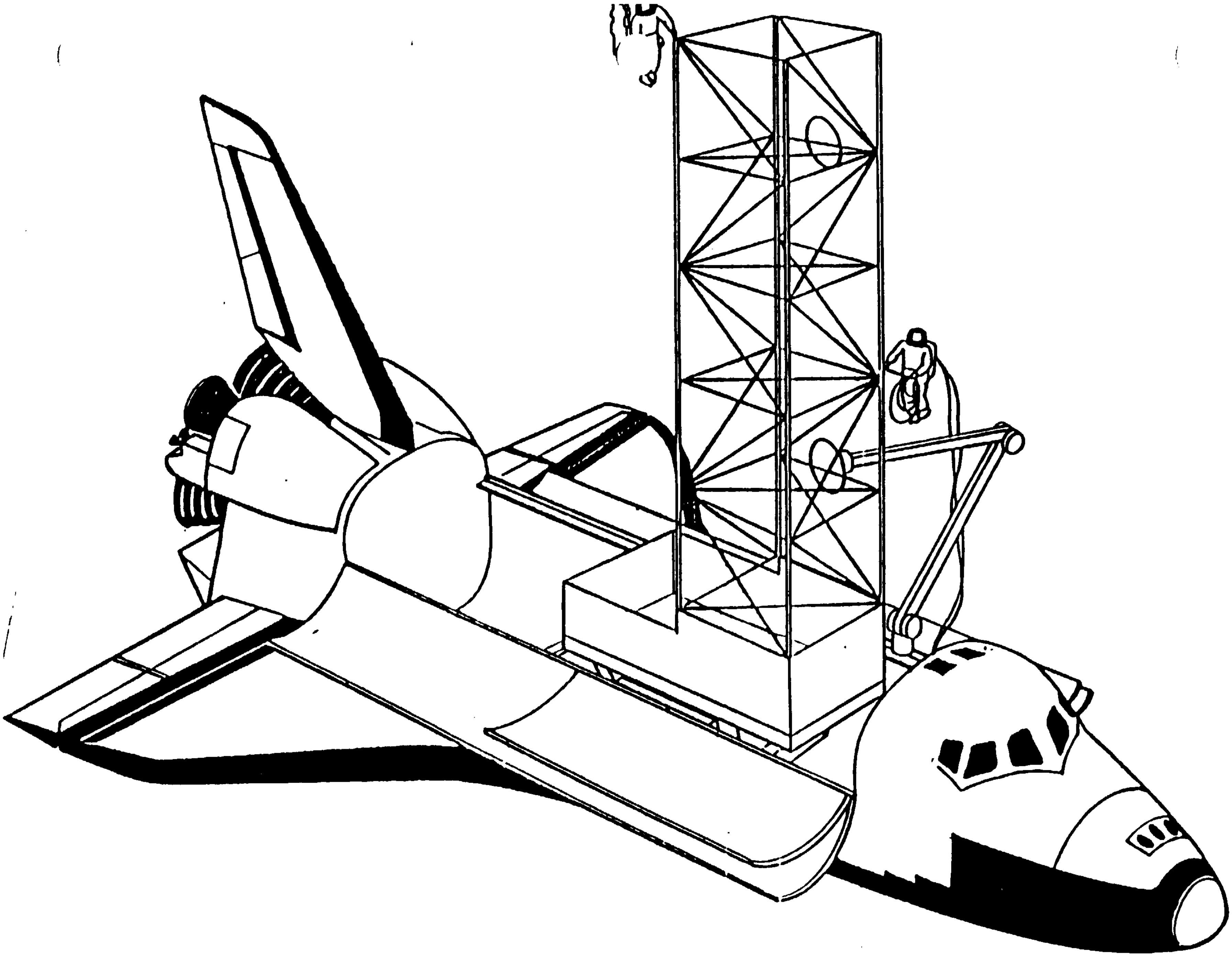


FIGURE 1 - SADE STRUCTURE

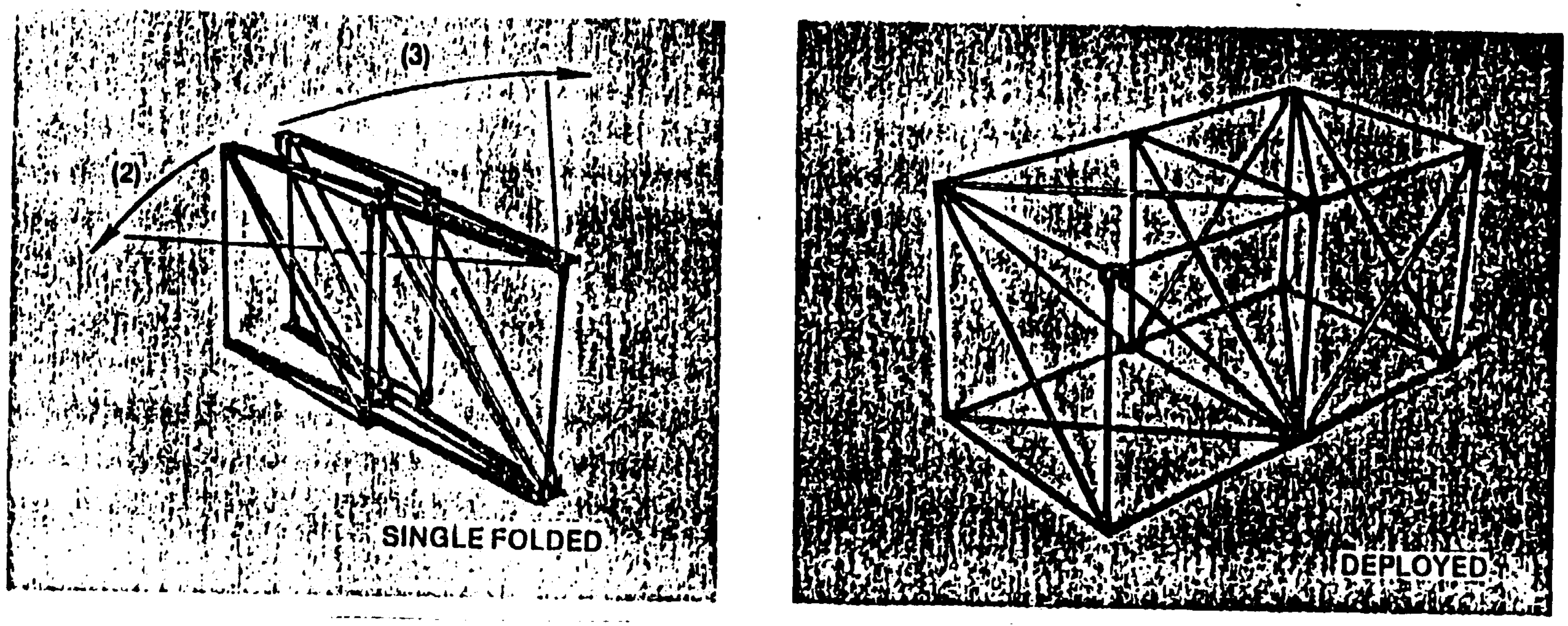


FIGURE 2 - DEPLOY SEQUENCE FOR SADE DEPLOYABLE MODULE

		RADIUS	THICKNESS	LENGTH	MASS	MOMENT OF INERTIA
DEPLOYED MODULE	LONGITUDINALS	3.175	0.089	300	1.438	4.31
	LATERAL/ VERTICALS	1.588	0.159	300	1.285	3.85
	DIAGONALS	1.588	0.159	424	1.816	10.88
INTERCONNECT	LIGHT LONGITUDINAL	1.905	0.089	300	0.844	2.53
	LIGHT DIAGONAL	1.905	0.089	424	1.193	7.15
	HEAVY LONGITUDINAL	1.905	0.635	300	14.907	44.72
	HEAVY DIAGONAL	1.905	0.635	424	21.069	126.25
UNITS		cm	cm	cm	kg	$kg \cdot m^2$

TABLE 1 - STRUCTURAL CHARACTERISTICS OF SADE STRUCTURE

		LaRC Snap Union	MIT Connector	Vought Clevis Coupler	Vought Autolock Coupler
Angular Tolerance	High			●	●
	Low	●	●		
Capture	Yes	●		●	●
	No		●		
Rigidizing	Yes				
	No	●	●	●	●
Latching	Yes		●		
	No	●		●	●

TABLE 2 - STRUCTURAL CONNECTORS FOR SADE STRUCTURE

3.2 Neutral Buoyancy Tests Prior to Flight

The neutral buoyancy tests that will be necessary prior to flight to attain the objectives listed in section 2, can be divided into three parts. The initial sequence of tests will be to define flight configuration hardware and an optimized set of assembly procedures , chosen so that all tasks can be performed in an identical manner in neutral buoyancy and in flight. This will enhance the correlation process significantly. The next test series will be devoted to verification of the hardware design and to further definition of the procedures. The third series of tests will be primarily to train the crew that will be assembling the structure on orbit. This is especially important so that a baseline timeline can be set up for comparison with the on-orbit results.

3.3 Test Procedures on orbit

The SADE experiment will take two six-hour EVA sessions to complete: one day to erect the structure, and one day to disassemble and stow it. The manpower allocation will be the same on both days: two crewmen will be EVA, one with the MMU, one without; one crewman on the aft flight deck, will control the video cameras, direct operations, and operate the RMS.

Experimental Approach

A preliminary set of procedures for erecting the SADE structure is shown in table 3, along with the primary data that is expected from each step. This is a "strawman" procedure that will serve primarily as a starting point for the early neutral buoyancy tests. Results of these early tests will no doubt modify the procedure to some extent, but the outline does indicate some of the more important operations that will be performed in flight:

- One deployable module will be unfolded using RMS, the other will be deployed with the MMU.
- Some of the manual assembly of structural elements in the interconnect structure will be performed with the subject in foot restraints, while some of it will have the subject out of foot restraints.
- Subjects will perform controlled alignment motions with structural elements both in and out of foot restraints, to evaluate the effect of mass and moment of inertia on body positioning, and to identify human control laws and applied torque levels as a function of foot restraints.
- A subject will translate along structure, once while carrying hardware and once without, so that loads imposed on structure by this process can be measured. Similarly, a subject with MMU will apply loads to the structure, to quantify these as well.

Experimental Approach

TASK	DATA OBTAINED ON
(1) UNSTOW TWO ELEMENTS OF INTERCONNECT CELL (LL, LD)	EVA OPERATIONS
(2) ROTATE EACH ELEMENT THROUGH 90° AND 180° IN FRONT OF CAMERA	HUMAN CONTROL LAWS & TORQUE LEVELS EFFECT OF MASS AND MOMENT OF INERTIA (WITH FOOT RESTRAINTS)
(3) INSTALL INTERCONNECT ELEMENTS ON FOLDED MODULE 1	ASSEMBLY IN FOOT RESTRAINTS CONNECTOR DESIGN
(4) REPEAT STEPS (1), (2), AND (3) FOR TWO MORE ELEMENTS OF INTERCONNECT CELL (HL, HD)	(AS LISTED ABOVE)
(5) ENGAGE GRAPPLE FIXTURE ON MODULE 1 WITH RMS	RMS OPERATIONS
(6) RELEASE MODULE 1 LAUNCH RESTRAINTS	EVA OPERATIONS
(7) DEPLOY MODULE 1 (CELLS 1 AND 2) WITH RMS	RMS DEPLOYMENT CAPABILITY

TABLE 3 - ASSEMBLY PROCEDURE: PART I

TASK	DATA OBTAINED
(8) UNSTOW 2 MORE ELEMENTS OF INTERCONNECT CELL (LL, LD)	EVA OPERATIONS
(9) SUBJECT B TRANSLATES ALONG MODULE 1 WITH LL ELEMENT	MANUAL TRANSLATION WITH HARDWARE ASSEMBLY LOADS
(10) SUBJECT A MOVES TO WORKSITE AT TOP OF MODULE 1 WITH LD	MMU TRANSLATION WITH HARDWARE
(11) SUBJECTS ROTATE ELEMENTS THROUGH 90° AND 180° IN FRONT OF CAMERAS	HUMAN CONTROL LAWS & TORQUE LEVELS EFFECTS OF MASS & MOMENT OF INERTIA (WITHOUT FOOT RESTRAINTS)
(12) CONNECT ELEMENTS TO TOP OF MODULE 1	ASSEMBLY WITHOUT BODY RESTRAINTS ASSEMBLY LOADS
(13) SUBJECTS TRANSLATE BACK TO LAUNCH ASSEMBLY PLATFORM	UNENCUMBERED MANUAL TRANSLATION UNENCUMBERED MMU TRANSLATION ASSEMBLY LOADS
(14) - (19) REPEAT STEPS (8) THROUGH (13) WITH REMAINING 2 ELEMENTS OF INTER-CONNECT CELL (HA AND HL)	(AS LISTED ABOVE)

TABLE 3 - ASSEMBLY PROCEDURE: PART II

TASK	DATA OBTAINED
(20) Subjects release module 1 holddowns	EVA operations
(21) RMS moves module 1 and interconnect cell up, aft, and outboard port	Manipulation of high moment of inertia, lightweight structure with RMS
(22) Release module 2 launch restraints	EVA operations
(23) Subject B deploys module 2, cell 1, manually	Use of unaided EVA for deployment
(24) Subject A deploys module 2, cell 2, using MMU	Use of MMU for deployment
(25) Subject B translates to top of module 2	Unencumbered manual translation
(26) RMS rotates module 1 180° and brings it into position over module 2	Manipulation of high moment of inertia with RMS
(27) Attach interconnect cell to module 2 with RMS guided by EVA crew	Integrated RMS/EVA assembly operations

TABLE 3 - ASSEMBLY PROCEDURE:PART III

3.4 Post Flight Tests

After the flight, the structural hardware used on orbit will be inspected to check for broken mechanisms. In addition, there is also the possibility of performing further neutral buoyancy tests if necessary; for example, if something unexpected happens in flight to prevent the crew from following established timelines.

4.0 DATA ACQUISITION

4.1 Time and Motion Data

Time and motion data for the two EVA crew members will be the primary source of the correlation data base. As such, collection of the necessary information for detailed time and motion analysis will be a high priority.

Besides serving as test conductor (reading off procedures to the EVA crew), the crew member on the aft flight deck will be responsible for direction and recording of video tape on the standard shuttle closed circuit television systems. Available camera angles will consist of the port and starboard forward and aft payload bay bulkhead mounts, and the RMS wrist and elbow cameras. It should be noted that RMS cameras will only be available for data collection when they are not required by the crew member in the port aft flight deck for RMS operations. Video tape data will be supplemented and backed up by a time lapse motion picture camera mounted in the aft flight deck, running at a rate no less than 1 frame/sec. This film camera will be mounted in such a location that a wide angle lense will pick up the maximum amount of crew activity, based on procedures developed in neutral buoyancy.

Since only one video channel may be recorded at a time, the interior crew member will be responsible for video mixing, as well as camera alignment. Experience with neutral buoyancy testing has shown that single-channel video can result in significant data loss, especially when two test subjects are working on separate tasks not in close proximity. In order to be assured of full correlation data, it will be necessary to have full time and motion data on each of the two EVA crew members. As part of the procedures checklist used in flight, closeups and significant camera angles will be listed for the camera operator. The time-lapse motion picture camera will be relied upon for data analysis of the second astronaut during video close-ups of the first, especially when the second is engaged in clearly evident activities such as translation. EVA timelines will be optimized to prevent the scheduling of tasks requiring video closeups when the other test subject is outside the vision angle of the film camera.

In addition to video and film records, crew members will be encouraged to give running verbal accounts of the assembly procedure, and their position on the timeline. This will allow another form of task time data, and will provide corroborating data for task times taken from the wide-angle view of the film camera. Actual time and motion analysis will be performed postflight: this procedure is covered in the following section.

Data Acquisition

4.2 Assembly Techniques

In addition to providing the majority of time and motion data, video tapes will also provide visual evidence of the relative ease of beam alignment, connector assembly, and so forth.

Body dynamics relates to the positioning of the body in weightlessness, and the human phase plane control laws for structural component alignment. While assembling the interconnect cell struts, the test subject will be required to rotate each strut through two 90 degree arcs, and one 180 degree one. These will be done such that the plane through which the beam is rotated is most nearly perpendicular to the sight vector from the recording video camera. The zoom setting of the camera will be such that the test subject's entire body will be visible on the screen. During post flight analysis, this will permit the beam position to be measured as a function of time, giving estimates for angular velocity by successive differencing and filtering. Image digitization of the resultant body motion will provide data on the forces applied, both to the beam and to the subject's work station on the structure.

Hardware evaluation and crew performance are highly subjective areas, which can best be quantified in terms of assembly time and difficulty. Completion times for each task will be found from videotapes, and by verbal marks given by the test subject when starting and completing the task. Difficulty of performing the task may be inferred by crew member cardiopulmonary rates, obtained through the EVA bioinstrumentation. It is important for this reason to have correlation marks of some sort between primary data collection media (video tapes and films) and the tapes of the bioinstrumentation readings. Crew qualitative evaluations will be given real time onto the audio track of the video tape, and discussed in more detail during post-flight debriefing.

4.3 Structural Data

Structural data will consist of strain gauge or load cell readings of stresses in the elements of the structure and of the launch assembly platform, along with accelerometer data from selected nodes and from the pallet (as an indicator of rigid-body orbiter motions). Sensors will be mounted to the structural elements prior to launch, to insure proper attachment procedures. Primary data recording will be performed by an LDEF experiment power and data system (EPDS), which receives data from sensors via wires connected by the EVA crew members. Since these wires cannot (in some cases) be attached until after the structure is complete, the load data during assembly will, if possible, be recorded on MIT solid state self-contained recorders (SSSCR's). These will be mounted on each structural element, and will be activated by the EVA crew. The EPDS will also have to be activated at the beginning of the run. After assembly, calibration of the sensors will be performed by loading the structure at a predetermined point by a known force (such as an MMU thrust at a specified node). Time of such loading will be noted by the test conductor, and entered into the flight log for calibration of the instrument recorders after the flight.

Data Acquisition

5.0 DATA ANALYSIS

5.1 Assembly Timeline Data Base

For the purposes of analysis, the entire SADE EVA procedure will be broken down into parts that are smaller and more specific at each level:

- First Level - the full set of extra-vehicular activities will be broken down into operations (e.g., cell deployment)
- Second Level - each operation will be broken down into component tasks (e.g., release launch restraints for module 1, cell 1)
- Third Level - each task will be broken down into component subtasks (e.g., activate latch safety release)

A data base will thus be established by recording the time for each operation, task, and subtask each time it is performed either underwater or on-orbit. A careful comparison can thus be made between the time required to perform a task in space and that required to perform the identical task underwater. In addition, time and effort spent on similar but different tasks in space (such as joining the various connectors) will be carefully studied.

5.2 Correlation Analysis

Simply comparing task times established in neutral buoyancy with those obtained on orbit will yield only a qualitative understanding of the difference between the two environments. A systematic statistical analysis of the flight experiment data, therefore, will also be performed to obtain quantitative correlation factors that are directly applicable to other neutral buoyancy tests and other assembly operations. This analysis will be carried out in the following manner:

- A chart showing timelines established on orbit in one column with the baseline timeline established in neutral buoyancy in a parallel column will be drawn up, so that it will be very apparent where the two procedures diverge and where they are most similar.
- Numerical factors for each subtask will then be calculated by computing the ratio of time spent on orbit for the subtask to time spent in neutral buoyancy for the same subtask. For example: if subtask 2.1.4, ingress foot restraints at work station B, takes 4:25 min on orbit and 3:36 min in neutral buoyancy, then the task time ratio for that specific subtask is 1.23.
- A more generally meaningful correlation factor will then be calculated by taking the average time spent for all the repetitions of a generic subtask. For example, if the foot restraints are ingressed 12 times during the assembly procedure the average time spent over these 12

repetitions will be compared with the same average established underwater.

- Multiple regression analyses will be performed for tasks which have more than one parameter. For example, ingressing foot restraints will require more or less time depending on local clearances, availability or absence of hand rails, and so forth. In this case, a time-variant linear regression analysis would be done, resulting in an equation for the time required to ingress foot restraints on orbit, as a function of the time required in neutral buoyancy. A variety of possible fit functions (logarithmic, power, exponential) will be tried for each of these multiple regressions, and the chosen model will be the curve fit with the highest coefficient of determination.
- Correlations will be performed for selected tasks based on MIT computer models of body motion in weightlessness. For example, the math model for translating a package indicates that the correct factor for nondimensionalizing the transport motion is

$$I(M+m)/MmDL$$

where I is the pitch moment of inertia of the EVA subject, M is the subject mass, m is the manipulated mass, and D and L are functions of the pressure suit dimensions. For manipulative translations, therefore, the nondimensionalized transfer times will be correlated between neutral buoyancy and space, as well as the raw times. Weighted linear regression correlation will also be performed, with weighting based on math model information of the specific task. This correlation procedure will apply to all tasks which can be accurately and reliably modeled. All correlations will include the coefficient of determination of the resultant curve fit.

- Based on the correlations obtained from the SADE flight, an EVA neutral buoyancy user's guide will be prepared, with details of extrapolation from SADE results to applicable correlation factors between general neutral buoyancy operations and expected timelines on-orbit.

5.3 Assembly Analysis

Body dynamics data will be digitized through the use of an X-Y digitizer attached to a video monitor, with a stop-motion video playback deck attached. Where necessary, data will be collected frame-by-frame: most of the data collection will be sufficient only to categorize gross body motions, and digitization frequencies will range down to .5 seconds/data point. Tracking targets on suit joints, backpack, and MMU will be necessary to allow location identification for sufficient accuracy in the digitizing process. Digitized body data will be stored on disk, and will be read into the computer for dynamic CAD reconstruction of body motion, comparison to math models to allow verification, and concurrent computer simulations with water drag to provide neutral buoyancy correlation independent of the time and motion data. At the same time, the beam alignment task data will be digitized, analyzed to provide beam angle as a function of time, differenced and filtered to provide angular velocity estimates as a function of time, and the phase plane control laws will then be generated, by plotting angular velocity versus angle.

<u>EVA design criteria</u> will be analyzed based heavily on crew comments, both during and after the assembly procedure. These comments will be the primary source of data for hardware evaluations from a user point of view. Video tapes will provide records of task time in performing the different tasks, while crew comments on the video tape will be used to find subjective reactions, as well as for refreshing the memories of the crew during post-flight debriefing. This information will be correlated with bioinstumentation sensor data to quantify the degree of difficulty of each assembly task. Learning on repetitious tasks will be analyzed in two ways: a power-law regresssion analysis on the task times (increase in speed) and on the net decrease in heart rate (decrease in difficulty). Productivity is the assembly rate at which the structure is completed. Fatigue will be found from the trends of heart rate or respiration as a function of time.

5.4 Structural Data Analysis

As mentioned earlier, structural data will be recorded on the LDEF experiment power and data system (EPDS), and possibly on the MIT solid-state self contained recorder (SSSCR), if that unit is qualified in time for flight. Wires for the EPDS sensors must be integrated into the structure, and connected by the EVA crew members. Data from strain gauges and accelerometers will be stored in essentially "raw" form in the EPDS.

With the development of the MIT system, data can be recorded in a variety of different forms, including digital waveform conversion, storage of Fourier coefficients, peak loads within a time frame, times of all structural loads exceeding a preset threshhold, and so on. Each SSSCR will be dedicated to its collection technique, and a number of such techniques will be tested for their utility in structural analysis. All sensors will be integrated on the structure prior to flight. Objectives of the structural loads study are to quantify loads placed on the structure by maneuvering around on it, RMS loads, loads during RMS and manual deployment, and loads in the structure due to a known force, such as a push on the structure at a given point with the RMS. A further objective of the structural analysis will be to identify damping, and to validate structural dynamic models with data returned from flight. Without the SSSCR's, only part of this data will be obtainable, since it will have to be stored in raw form, rather than partly conditioned, and will thus take up more room on tape. Under these conditions, for example, only some loads data will be storable, yielding little or no information on structural dynamics and damping in weightlessness.

Data Analysis

6.0 BENEFITS FROM SADE

The benefits from performing the structural assembly demonstration experiment include

- An initial demonstration of the capability to both deploy and assemble structures in space from the shuttle
- Statistically meaningful data to allow correlation analysis between neutral buoyancy and zero-g for each category of task and subtask used in the SADE experiment
- A data base for future EVA planning, with experience for timeline construction of future EVA procedures
- Quantitative data on the control laws used by humans in space, and correlations of manipulative times to allow the estimation of the relative significance of mass and moment of inertia on-orbit
- Validation of math models of the human body in weightlessness, and indications of the existence of an instinctive adaptation to the weightless environment
- Human factors evaluation of all structural hardware and supporting equipment, including comparative evaluation of four specific joint designs, and qualitative conclusions as to the more favorable choices and importance of connector design criteria

- Structural loads data on components of the assembled and deployed structure during and after completion, and stresses induced by static and dynamic loading conditions
- Tests of the utility of manual and MMU aided deployment of large structures.
- Verification of the use of the RMS in structural deployment applications.